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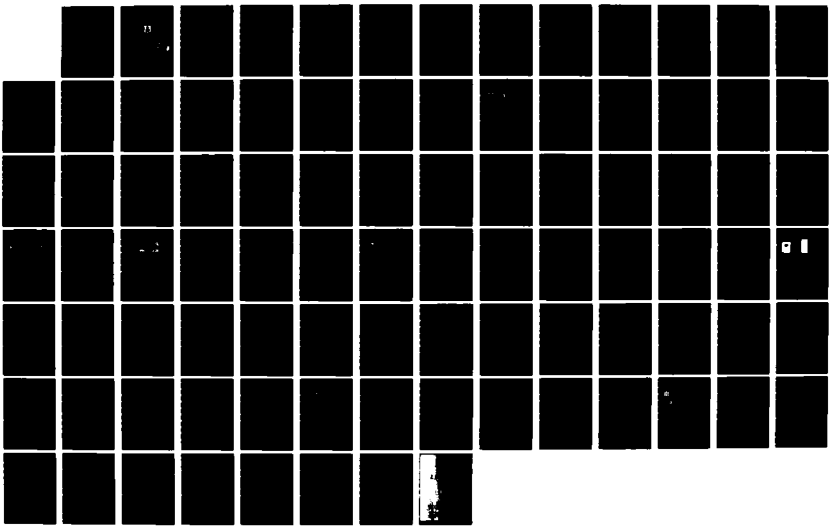

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FOREIGN TECHNOLOGY DIVISION

DISCHARGE WITH HOLLOW CATHODE

(Selected Chapters)

by

B. I. Moskalev

UNEDITED MACHINE TRANSLATION

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DISCHARGE WITH HOLLOW CATHODE (Selected Chapters)

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U. S. BOARD ON GEOGRAPHIC NAMES TRANSLITERATION SYSTEM

Block	Italic	Transliteration	Block	Italic	Transliteration
А а	*А а*	A, a	Р р	*Р р*	R, r
Б б	*Б б*	B, b	С с	*С с*	S, s
В в	*В в*	V, v	Т т	*Т т*	T, t
Г г	*Г г*	G, g	У у	*У у*	U, u
Д д	*Д д*	D, d	Ф ф	*Ф ф*	F, f
Е е	*Е е*	Ye, ye; E, e*	Х х	*Х х*	Kh, kh
Ж ж	*Ж ж*	Zh, zh	Ц ц	*Ц ц*	Ts, ts
З з	*З з*	Z, z	Ч ч	*Ч ч*	Ch, ch
И и	*И и*	I, i	Ш ш	*Ш ш*	Sh, sh
Й й	*Й й*	Y, y	Щ щ	*Щ щ*	Shch, shch
К к	*К к*	K, k	Ъ ъ	*Ъ ъ*	"
Л л	*Л л*	L, l	Ы ы	*Ы ы*	Y, y
М м	*М м*	M, m	Ь ь	*Ь ь*	'
Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

*ye initially, after vowels, and after ъ, ь; e elsewhere.
When written as ё in Russian, transliterate as yё or ё.

RUSSIAN AND ENGLISH TRIGONOMETRIC FUNCTIONS

Russian	English	Russian	English	Russian	English
sin	sin	sh	sinh	arc sh	$\sinh^{-1}$
cos	cos	ch	cosh	arc ch	$\cosh^{-1}$
tg	tan	th	tanh	arc th	$\tanh^{-1}$
ctg	cot	cth	coth	arc cth	$\coth^{-1}$
sec	sec	sch	sech	arc sch	sech^{-1}
cosec	csc	csch	csch	arc csch	csch^{-1}

Russian	English
rot	curl
lg	log

GRAPHICS DISCLAIMER

All figures, graphics, tables, equations, etc. merged into this translation were extracted from the best quality copy available.

DISCHARGE WITH HOLLOW CATHODE.

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Chapter Five.

ARC DISCHARGE WITH HOLLOW CATHODE.

... Luce and Ruark investigated several different methods of dissociation. Luce proposed to utilize for this an arc discharge. As a result of its experimental work in the beginning 1956 was more or less randomly opened the fundamentally new type of arc discharge:.

Amasa S. Bishop [154].

As has already been mentioned, arc discharge with the hollow cathode was discovered by Luce during the study of the different methods of dissociating the deuterium.

First Luce utilized for dissociating the beam of deuterium [42] the arc discharge which although had hollow cathode, the effect of hollow cathode in it was absent. Arc began from bright cathode spots small according to the size/dimension; they rapidly were moved over butt end of the cylindrical thick-walled graphite cathode, through which first for the triggering was supplied argon, and then gas

supply ceased. From each cathode spot went the bright thin compressed by external magnetic field filament of discharge. Simultaneously were observed several filaments moving following the cathode spots which formed the visible positive column with the diameter, approximately/exemplarily equal to the diameter of cathode conductor. This "filament" type of discharge rapidly corroded as a result of the erosion the end/face of cathode and characteristic of discharge itself due to the wandering of cathode spots were unstable.

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When carbon arc did not justify itself from the point of view of its suitability for the planned thermonuclear experiment, then at one time it seemed that resolution of problem could ensure a similar arc, which only works not in the vapors of carbon, but in the deuterium (see Chapter 10).

After replacing graphite cathode to the tungsten and bloing through it instead of argon deuterium, Luce revealed for the first time the effect of hollow cathode in some modes/conditions of the work of deuterium arc. In this case the discharge appeared within the cavity, leading to the strong heating of the section of cylindrical tungsten cathode, with sizes/dimensions several square centimeters: thermoemission from this section it provided arc current. A similar

effect can be obtained, also, in the carbon arcs, that subsequently described Michelson [76] by the major advantage of the effect of hollow cathode in the arc there was the sharp decrease of erosion of cathode material. Arc could work during 10-15 min with the current 200 A (current density 25000 A/cm²), moreover in view of the absence of the stray cathode spots its work was stable.

Luce, who discovered arc discharge with the hollow cathode, was interested in essence by the possibilities of its use: first in the thermonuclear experiment, and then for engineering the arc rocket space engine (see Chapter 10 and 11). The first attempt to outline special features/peculiarities of this type of discharge from the point of view of its mechanism made Rose in [77]. Let us dismantle/select the fundamental conclusions of this work which are based on the study of the experimental material, obtained during the use of a hollow cathode from graphite.

Rose immediately noted the great similarity in the phenomena of arc discharge to the hollow graphite cathode also of the glowing discharge with the hollow molybdenum cathode, working at the high current densities [53]. Most vividly it is expressed in the fact that after the prolonged combustion of discharge the initially cylindrical cathode cavity acquires characteristic egg-shaped form.

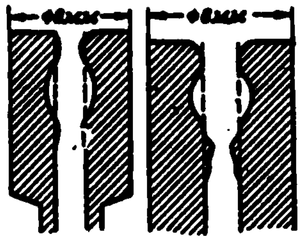

Fig. 5.1. Form of cavities, formed by the arc discharge in the initially cylindrical cathode from carbon.

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Fig. 5-1 shows schematically the cavities, formed in the arc discharge with the hollow cathode which worked in the atmosphere of argon. Their resemblance to the cavities, formed by the hollow cathode discharge, is obvious (see Fig. 3-61).

Further Rose showed that the differences in the values of operating pressures and voltages/stresses between both discharge forms are not very great and therefore for the analysis of phenomena in this discharge it is possible to use some models of the glowing discharge. Especially this is correct for the arc with the low currents, which can be considered stable transitional form from the glowing discharge to the arc. After taking as the base for the analysis work [75], Rose assumed that the charge density within the cavity is sufficiently great for forming the region of a potential

drop in the layer, which separates/liberates cathode from the plasma. The layer in question is sufficiently fine, so that the electrons, which emerge from the cathode, pass it without the collisions.

Then, considering that the ions, which are formed in the plasma, move to the cathode as a result of diffusion, it is possible to calculate ionic density N_i in the plasma and thickness of the layer in cathode d_k. Evaluations/estimates, made in [77], gave for the current 15 A (current density 80 A/cm²) value $N_i=4\cdot10^{16}$ 1/cm³ and $d_k=3\cdot10^{-4}$ mm which the author estimates as those approximated. However, in any event of them it follows that the approximation/approach of thin layer accepted is acceptable. Consequently, electrons, after passing the layer of cathode drop without the collisions, then lose entire their energy in the plasma for the ionization and excitation. However, due to a smaller voltage drop in the layer (approximately/exemplarily 50 V or below in comparison with 200 V for the glowing discharge) a number of formed ions and photons too little in order to support discharge by means of γ-processes, and therefore the mechanism of secondary processes in the arc with hollow cathode must be different, than in the glowing discharge. If for vapor Mo-Ne required for maintaining the discharge with a cathode drop in higher than 100 V coefficient γ=0.24 still and stands on the face of real, then for vapor C-Ar in the case in question it is necessary γ=0.5 or above that completely cannot be

provided with graphite at a room temperature. There are three possibilities for changing state of affairs.

1. Secondary-emission coefficient γ strongly increases with increase in temperature of cathode.

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2. Secondary-emission coefficient γ strongly increases due to increase in electric field in cathode.

3. Cathode is heated to such temperatures, that becomes essential process of thermoemission.

The author [77] notes that for the evaluation of a comparative role of these possibilities it is thus far still small data. Relative to the first process nothing is known.

Calculation of field in cathode gives value $1.3 \cdot 10^6$ V/cm, which already can give noticeable effect for the emission of electrons from the cathode. Most reliably can be designed the currents, caused by thermoemission.

Utilizing a formula for the thermoemission in the form

$$j_e = 5{,}97T_K^2 \exp(-4{,}57 \cdot 10^4/T_K), \qquad (5\text{-}1)$$

corresponding to work function 3.93 eV, we obtain the following numerals: 3000°K, 10.5 A/cm^2; 3300°K, 62 A/cm^2; 3500°K 153 A/cm^2; 4000°K, 1070 A/cm^2. Consequently, if for the current 15 A the fundamental process, which leads to the output of electrons from the cathode, thermoemission, then the temperature of cathode surface T_K must be $T_K \geqslant 3\,300°$K. Unfortunately, the temperature of surface within the cavity it is difficult to measure. Measurements of the temperature of external surface on the low currents gave value ≥2150°K. High rate of evaporation of the surface layer of carbon when $T_K = 3\,300°$K cannot serve as reason against the possibility of the realization of this temperature in the hollow cathode, which works sufficiently long time, because neutral atom has few chances to leave cavity and returns in the form of ion to the cathode. Consequently, it is very probable that the thermoemission plays considerable role in the maintenance of the discharge which in that case with good reason can be considered arc.

Getty and Smullin [78], experimenting first with the graphite cathode as in [76, 77], then found that for arc-striking with the hollow cathode in the range of currents 2-80 A are very convenient the thin-walled jointless tantalum tubes. As a result of the low speed of pulverization/atomization and evaporation of tantalum they, in spite of the small thickness of wall (on the order of 0.1 mm),

they can work long time (about 8 h).

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This fact served as base for the intense investigation of the properties of the plasma column, ejected by a similar arc with the hollow tantalum cathode into vacuum chamber with external longitudinal magnetic field [78].

Phenomena in the arc discharge with the hollow cathode from the refractory metal are so peculiar that first in the literature there was a tendency to consider as the its completely specific type of discharge and name "arc with the hollow cathode" was proposed "after the lack of the best" [79]. However, this, of course, is not so. Let us turn to the history.

In 1916 Paschen worked with spectral source, in which was utilized the discharge with the "hot" hollow cathode. The strong heating of cathode as the most characteristic feature of discharge with the hollow cathode noted in 1923 Gunterschulze (see Chapter 2). If we do not take special measures for cooling, then under some conditions material of cathode enters gas phase in such quantity, that vapors of electrode to a considerable degree cause flashover characteristics: appearance, electrode voltage, etc. In 1926 Schuler

[19] it described the conditions in which it is possible to obtain the discharge in the pure/clean vapors of metal. Hollow cathode for this purpose had external preheating by space heater. Inside the cathode was embedded the sample/specimen of metal. First into the tube was admitted inert gas, but then it was evacuated. The discharge in the hollow cathode, after being begun in the presence of inert gas, it continued also after its evacuation already in the pure/clean vapors of metal. The resemblance of this discharge to the discharge, described by Michelson [76], is obvious.

An even larger resemblance is observed between the "discharge with the hot hollow cathode" and the arc with the hollow cathode, which works not in the vapors of the material of cathode, but in the duct of gas. In [80] is described the device/equipment in which hollow graphite cathode was incandesced by discharge to temperature on the order of 2000°C. In [36] it is noted, that the maximum temperature of hollow cathode occurs in the circular zone, distant up to certain distance from the open end/lead of the cathode, on both sides from this hot ring the temperature drops. The same characteristic change in the temperature along the cathode was noted also for the arc with hollow cathode [79]. Resemblance in the forms, taken by cathodes after the continuous operation of discharges, has already been noted by us earlier. Finally, voltage/stress in the glowing discharge with the hot hollow cathode with the high currents

can be very strongly lowered. In [81] are described the modes/conditions, when the voltage/stress of the hollow cathode discharge composed 70 V. Is certain, this the already transitional form between the glowing and arc discharge, which is completely identical to a similar transitional form, described during the study of arc with the hollow cathode by Rose and dismantled/selected by us somewhat earlier. Difference here only in the method of the realization of the circulation of the gas through the system. In the experiments with the glowing discharge the gas circulated in the system, passing/avoiding cathode cavity; in the experiments with the arc gas it entered into the system through the hollow cathode. This difference is completely unessential with currents on the order of 2 A and voltages/stresses on the order of 50 V [1], that was later checked by straight/direct experiment [79].

FOOTNOTE [1]. These numerals relate, of course, only to the concrete/specific/actual examined systems. ENDFOOTNOTE.

However, this difference is decisive if we increase the currents, passing through the discharge gap.

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With the usual method of the circulation accepted in the practice of

spectroscopy (gas is not pumped through through the cathode cavity) an increase in the current leads to abrupt transition/junction into the usual arc discharge with the cathode spot. When working gas is pumped through through the cathode cavity, an increase in the current leads to the gradual transition into the arc with the hollow cathode, which is characterized by the voltage/stress of combustion on the order of 30 V [1], by current on the order of hundreds and even thousands of amperes and by absence of cathode spot.

FOOTNOTE [1]. In [78] it is shown that only approximately/exemplarily half of this voltage/stress can fall to the cathode drop which, thus, is located near the first ionization potential of argon. ENDFOOTNOTE.

This, it becomes possible, because the decrease of gas density, which occurs usually with an increase in the temperature of gas within the cavity, is compensated by its artificial increase as a result of the circulation of the gas through the cathode.

Moreover if arc works in the external longitudinal magnetic field, in the region out of the cathode is formed the plasma jet, which in the modes/conditions with the high currents begins to work as "ionic pump". Neutral atoms of residual gas, which intersect as a result of their thermal agitation plasma jet, are ionized and then they drift in the electric field along the jet, until they hit inside

the hollow cathode where they subsequently are neutralized during the collision with the cathode. This process leads to the evacuation of gas from the region out of the cathode and additionally increases the density of plasma within the cavity (see Chapter 10). As a result of acting these factors conditions within cavity always remain within the framework of that range with which mean free path for ionization is lower than diameter of hollow cathode. Under these conditions, as already mentioned in Chapter 1, was feasible the high-current discharge with the hollow cathode without cathode spot, while with the decrease of gas density is observed the tendency toward the formation/education of cathode spot.

Thus, arc with the hollow cathode is not gas-discharge form, completely different from those investigated it is earlier discharges with the hollow cathode; however under the normal conditions to obtain this arc is difficult and only the circulation of the gas through the cathode cavity makes possible the lung its realization.

Let us examine the special features/peculiarities of the work of arcs with the hollow cathode, following in essence work [79], in which for the experimental study was used the installation, schematically depicted in Fig. 5-2. The circulation of gas in it is realized in vacuum chamber with a diameter of 10 cm and with a length of 1.5 m. The chamber/camera is made from the glass pyrex, with

exception of center section which is made from brass and is cooled by water. Vacuum sliding seals make it possible to regulate the distance between the cathode and the anode during the work of arc. The evacuation of the gas, which enters the chamber/camera, is realized by three diffusion pumps with a productivity of 700 l/s each, which work on the general/common/total forevacuum pump.

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Gas from the metallic tank/balloon through the reducer and the flow regulator enters vacuum chamber directly through the cathode cavity.

The parts of cathode node are shown in Fig. 5-3. Screen from nitride is borzoi it blocks erosion of the copper holder of cathode it facilitates striking of the arc, preventing formation/education in the stage of the triggering of cathode spot on the copper surface of holder and without allowing/assuming the penetration of plasma into the space behind the cathode. The rate of the circulation of gas 0.05-2.0 $cm^3 \cdot atm/s$, which provides pressure in vacuum chamber 10^{-3} mm Hg, while the gas pressure in the foundation of cathode with the work of arc is characterized by the values of 5-20 mm Hg. Cooling cathode node is realized by the flow of water, passing through radial clearances of the holder of cathode. Anodic node is analogous to cathode, only instead of the cylindrical cathode in it is fastened/strengthened the continuous copper anode.

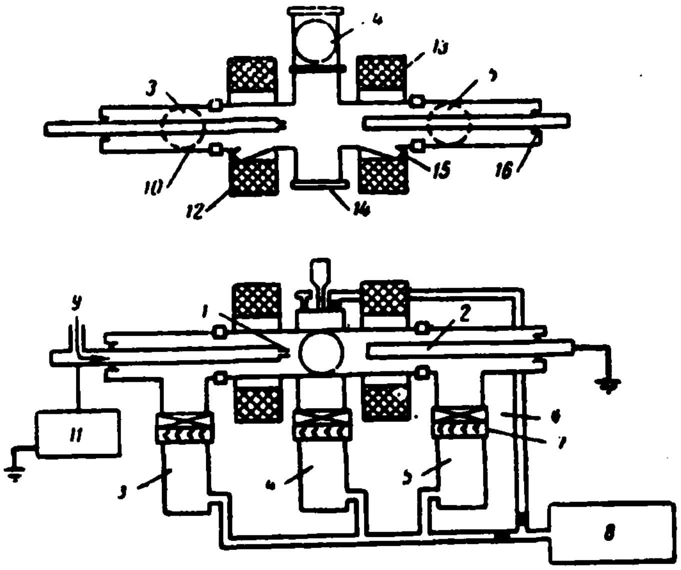

Fig. 5-2. Diagrammatic representation of experimental installation for the investigation of arc discharge with the hollow cathode. 1 - hollow cathode; 2 - anode; 3, 4, 5 - diffusion pumps; 6 - lock; 7 - reflector; 8 - fore pump; 9 - gas supply; 10 - glass tube; 11 - power supply; 12, 13 - solenoids; 14, 15 - inspection windows; 16 - sliding vacuum seals.

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As the supply of power of the described installation served two connected consecutively/serially d c arc welders on 300 A each. Two solenoids, shown in Fig. 5-2, could provide longitudinal magnetic field with the intensity/strength in the center of chamber/camera to 1000 G. The majority of characteristics was taken/removed in the

presence of external magnetic field. However, arc with the hollow cathode can work, also, without the magnetic field, which, strongly changing conditions for the passage of current in the space between the cathode and the anode, nevertheless barely affects the mechanism of processes in the cathode cavity.

For the stable work it is necessary that the ratio of the length of cathode to its diameter would be not less than 6, but the walls of cathode must be sufficiently thin so that 90-95% of energy, which arrives at the cathode is scattered in the form of radiation. The most suitable materials for the cathode are the refractory metals: tantalum or tungsten. If the tantalum cathode with a diameter of 3 mm is equipped with radiators, then it can work with the current 100 A many hours without the damages and is short-term with the currents 270 A.

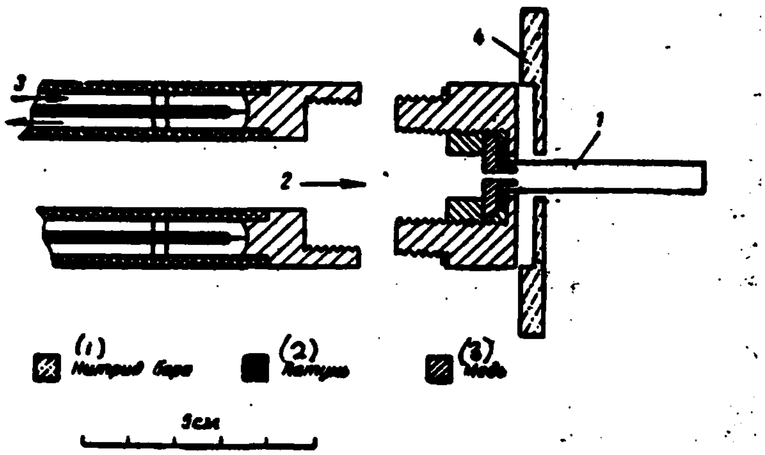

Fig. 5-3. Device/equipment of the cathode node of the installation, shown in Fig. 5-2. 1 - hollow cathode; 2 - flow of gas; 3 - cooling water; 4 - screen.

Key: (1). Nitride of boron. (2). Brass. (3). Copper.

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In order in the described system to excite the arc discharge with the hollow cathode it is necessary to fulfill the series/row of conditions. If they are not performed, then either arc cannot be ignited or appears the vacuum arc in the vapors of metal which damage the cathode. These conditions are reduced to the following: pressure in the chamber/camera must be several microns of the mercury column, longitudinal magnetic field must compose several hundred gauss or

more, the flow of gas must have a rate of approximately 1 $cm^3 \cdot atm/s$, must be applied constant voltage between the cathode and the anode 70-140 V is created preliminary ionization by high-frequency oscillator. With the simultaneous observance of the conditions indicated between the cathode and the anode flows the current into several amperes, and cathode is heated to temperature of 700-900°C. Then current abruptly grows/rises to the value, limited by external diagram, and simultaneously on the cathode appears the incandescent to temperature of 2000-3000°C zone with length in several cathode diameters. This zone is distant from the end/lead of the cathode to one-two diameters and is the characteristic feature of arc discharge with the hollow cathode.

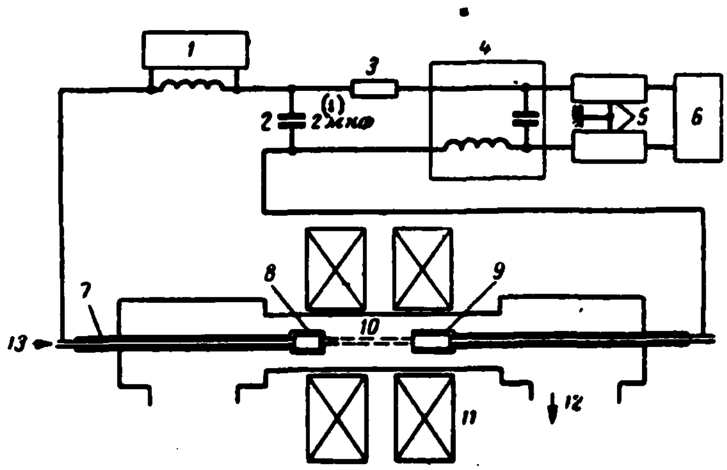

Fig. 5-4. Schematic diagram of the device/equipment, used for the investigation of arc discharge with the hollow cathode. 1 - high-frequency alternator; 2 - capacitor/condenser for the connection/communication of oscillator with the discharge gap; 3 - resistor, connected in series with the discharge; 4 - filter of low frequencies; 5 - filter of high frequencies; 6 - generator of direct current; 7 - insulators; 8 - hollow cathode; 9 - anode; 10 - discharge; 11 - solenoids; 12 - evacuation; 13 - gas.

Key: (1). μF.

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After this the high-frequency igniting block can be disconnected. Being ignited, arc discharge with the hollow cathode it can work over a wide range of operating conditions.

Representation about the operational conditions can be obtained from Table 5-1, comprised on the basis of the experimental data of works [79, 82]. The installation for arc-striking with the hollow cathode, used in [82], in essence is analogous described above. Some differences were only in the method of feed. The electrical circuit of discharge, used in [82], it is shown in Fig. 5-4.

The volt-ampere characteristics of arc with the hollow cathode depend on sizes/dimensions and material of cathode, working gas, velocity of his circulation and do not depend on form, sizes/dimensions and material of the anode, if electrodes are arranged/located on one axis. Figure 5-5 [79] shows effect on the volt-ampere characteristic of the thickness of tantalum cathode, are here given temperature curves. In [82] it was established that the volt-ampere characteristic with a good degree of accuracy can be calculated from the equations which for tantalum are expressed as

$$I = 6{,}7 S_{\text{к.эф}}\, j(T);\quad V = 0{,}43\,\frac{W_{\text{к}}(T)}{j(T)}; \qquad (5\text{-}2)$$

for the tungsten as

$$I = 1{,}8 S_{\text{к.эф}}\, j(T);\quad V = 1{,}6\,\frac{W_{\text{к}}(T)}{j(T)}. \qquad (5\text{-}3)$$

here $W_{\text{к}}(T)$ — the power, emitted by cathode;

j(T) - the density of electronic current of saturation at a

temperature T;

$S_{к.эф}$ — area of the effective surface of cathode.

Table 5-1.

(1) Внутренний диаметр катода, мм	(2) Рабочий газ и материал катода	(3) Скорость прокачки газа при атмосферном давлении, $см^3/сек$	(4) Ток дуги, а	(5) Напряжение дуги, в	(6) Температура катода, °K	(7) Мощность, рассеиваемая анодом, %
3	(8) Аргон, Ta	0,1	30	30,2	2710	61
3	(9) Гелий, Ta	0,95	30	78	—	75
(10) 12,7	(8) Аргон, Ta	1,40	106	36	2460	42
От 10 до 16	(8) Аргон, Ta	—	30	75	—	—
От 10 до 16	(11) Водород, W	—	40	210	—	—

Key: (1). Inner diameter of cathode, mm. (2). Working gas and material of cathode. (3). Rate of circulation of gas with atmospheric pressure, cm^3/s. (4). Arc current, A. (5). Voltage/stress of arc, V. (6). Temperature of cathode of °K. (7). Power scattered by anode, %. (8). Argon. (9). Helium. (10). From 10 to 16. (11). Hydrogen.

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In [82] was also experimentally determined the potential gradient in the plasma jet, ejected by hollow cathode, with the intensity/strength of longitudinal magnetic field 2150 Oe. Its values lie/rest within the limits of 0.43-1.29 V/cm with the decrease of discharge current from 50 to 20 A.

Since the axial electric fields and energy losses in the plasma jet, which proceeds from the cavity of cathode, are small, it is possible to attempt to compose energy balance within the cathode,

utilizing instead of the value of cathode drop the measured voltage/stress between the cathode and the anode.

Let us compose the energy balance for the mode/conditions, defined by the first line Table 5-1 in the manner that this was done in [79].

Let us introduce the following assumptions:

1. Electronic current I_{ec} of cathode consists of two parts; one part I_{ec1} reaches the anode without the exciting or ionizing collisions with the atoms of gas within the cathode, another part I_{ec2} completes similar collisions.

2. Energy of electrons in I_{ec1} corresponds to voltage/stress U_{ak}, applied to discharge gap energy of electrons in I_{ec2} is characterized by temperature of plasma T_e and it corresponds to voltage/stress which we will designate U_T.

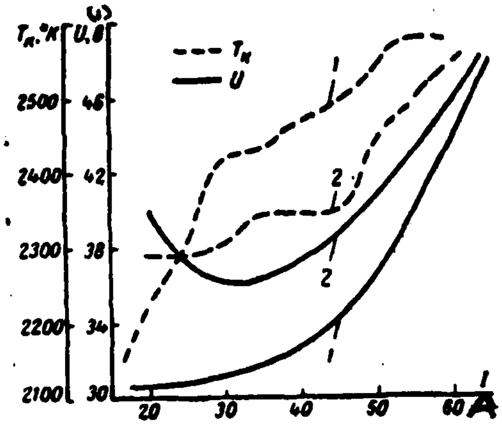

Fig. 5-5. Dependences of voltage of combustion (unbroken curves) and temperature of cathode (dotted curves) from current of discharge for different thickness of cathode wall s. 1 - s=0.51 mm; 2 - s=0.25 mm.

Key: (1). V.

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3. Electronic current $I_{ев}$ appearing as a result of ionization of gas, is also characterized by energy, which corresponds U_T.

4. All ions in the final analysis return to cathode (some ions emerge from cathode against electric field strengths under action of pressure gradient, but they, as it is assumed, then again they return to cathode as a result of evacuating action of plasma jet after their diffusion from plasma jet on walls of vacuum chamber and

neutralization). Consequently $I_{eg}=I_{ic}$ (Fig. 5-6).

Under the made assumptions power W_a, scattered by the anode, is equal to:

$$W_a = I_{ec1}U_{ak} + (I_{ec2}+I_{eg})U_T, \qquad (5\text{-}4)$$

and the total current

$$I = I_{ec1}+I_{ec2}+I_{eg}. \qquad (5\text{-}5)$$

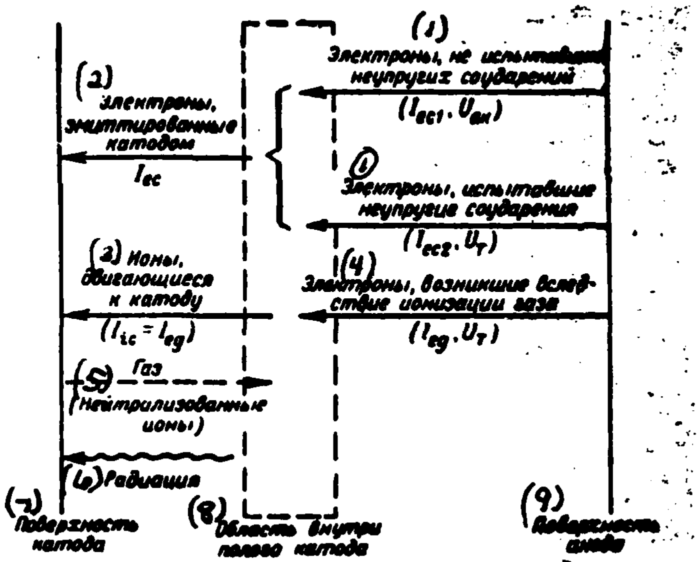

Fig. 5-6. Diagrammatic representation of processes in the arc discharge with the hollow cathode. Arrows/pointers designated the flows of the charged/loaded particles, neutral particles and photons. The direction of arrows/pointers in the case of the flows of the charged/loaded particles corresponds to direction of flow, caused by these flows.

Key: (1). Electrons, which did not experience inelastic collisions. (2). Electrons, emitted by cathode. (3). Ions, which move to cathode. (4). Electrons, which arose as a result of ionization of gas. (5). Gas. (neutralized ions). (6). Radiation. (7). Surface of cathode. (8). Region within hollow cathode. (9). Surface of anode.

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Since working the voltage/stress is small, all ions are formed by rapid electrons from I_{ec2}. Such electrons can ionize 1 time, but unlikely so that they would ionize twice, taking into account the competing processes of excitation. Then

$$I_{ic}=I_{eg}=\frac{I_{ec2}}{1+\frac{\bar{\sigma}_x}{\bar{\sigma}_i}}, \qquad (5\text{-}6)$$

where $\bar{\sigma}_x$ — effective cross section of the processes of excitation, which do not lead in the final analysis to the stepped ionization;

$\bar{\sigma}_i$ — effective cross section for the straight/direct and stepped ionization.

Equations (5-4)-(5-6) can be

$$I_{ic}=\frac{(IU_{ax}-W_a)}{(U_{ax}-U_T)\left(2+\frac{\bar{\sigma}_x}{\bar{\sigma}_i}\right)} \qquad (5\text{-}7)$$

and

$$I_{ec}=I-I_{ic}. \qquad (5\text{-}8)$$

Equations (5-7) and (5-8) make it possible to calculate I_{ec} and I_{ic} if other values are known. Accepting [79] $\bar{\sigma}_x/\bar{\sigma}_i=1$, $U_T=1$ V and taking remaining values from the first row Table 5-1, we obtain $I_{ec}=25{,}9$ A $I_{ic}=4{,}1$ A. The authors [79] assume that if we calculate the current, which corresponds to the fully ionized flow of gas, through the

cathode, then is obtained value 0.4 A, by an order less than the actual ion current to the surface of cathode, and therefore each atom is ionized within the hollow cathode and is neutralized on the cathode surface several times before it will leave the cavity. This confirms the assumption, made earlier by Rose [77] that the chances of neutral atom to traverse the cavity of cathode without the ionization are small.

If one assumes that each electron into $I_{ез}$, which did not experience the ionizing collision, it excites 2 times and that each photon bears energy 14 eV, then it is obtained, which from the total power of 906 W, spent on the maintenance of discharge, 304 W is scattered by cathode, 548 W is scattered by the anode and 54 W it falls for the radiation/emission and the diffusion from the plasma jet, and also for the ohmic heating of cathode tube.

In the dismantled/selected higher example the calculated ionization-current ratio to the electronic on the surface of cathode was 0.16. Similar computations, carried out in [79] for different modes/conditions, showed that also in the majority of the cases relation I_{u}/I_{e} is small. This speaks, that the fundamental reason for the emission of electrons from the cathode is the thermoemission (is probable the presence and autoelectronic emission), and emission under the action of the impacts of positive ions plays secondary

role. However, a precise mechanism of emission in the arc with the hollow cathode (as it is noted by the authors [79]), at the present time still little known.

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Chapter Six.

HIGH-VOLTAGE DISCHARGE WITH HOLLOW CATHODE.

At an insignificant pressure of gas in the hollow cathode were obtained two various forms. One of them ... is characterized by the relatively large current strengths and by the low cathode incidence/drop, having all properties of the usual glowing discharge. With another - the space within the cavity is filled with more uniform light/world without the sharp boundaries, dark/nonluminous space is in no way evident, current strength much less, but voltage/stress much more than in the first form.

Gunterschulze (on 2 December, 1929) [L. 23].

Investigating the effectiveness of the hollow cathode discharge [23] on the experimental instrument, shown in Fig. 3-2, Gunterschulze revealed/detected following phenomena. At a pressure of hydrogen 0.26 mm Hg (distance between the cathodes was 1 cm) and a

voltage/stress between the cathode and anode 400 V increase of current from 100 to 53 mA (with the aid of high external resisting in the feed circuit) lowered the voltage/stress of combustion to 350 V. Reduction in current from 53 to 30 mA produced an increase in the voltage/stress of combustion, so that it again achieved 400 V. During an attempt at further reduction in current the discharge abruptly passed into the new combustion behavior: 6 mA and 600 V. The characteristic external feature of new mode/conditions was the absence of dark space of the cathode drop, which is sharply delimited from the plasma within the cavity.

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Considering that the transition from the high currents to small during the selection sufficiently high resisting can be continuous, Gunterschulze assumed that the new form of discharge observed by it corresponds to the "preliminary stage of the glowing discharge, anomalously intensified due to the effect of hollow cathode". The vagueness of this formulation and the absence of any detailed study of the characteristics of new discharge form in [23] led to the fact that in somewhat other modifications a similar discharge was opened again at least twice: one time by circle [24] and for the second time by Van Paassen and Allen [83]. With respect what have stated we into Chapter 1, forms of discharge, described in [23, 24,

83], we was carried to the high-voltage (cathode-ray/electron-beam) discharge with the hollow cathode. From Fig. 1-2 it is evident that it can exist at low pressures for the sufficiently low currents. In certain range of currents stable are both forms: glowing and high-voltage. and actually/really, Gunterschulze [23] observed, that the high-voltage discharge during the creation in the gas-discharge gap/interval of supplementary ionization from the coil of T passed into the hollow cathode discharge. On the contrary, if we interrupt circuit during the combustion of the glowing discharge and to again lock it, then is installed high-voltage discharge with the hollow cathode. Gunterschulze noted also that with the decrease of pressure the high-voltage discharge with the hollow cathode already cannot be transferred into that glowing.

The high-voltage discharge with the hollow cathode in the conditions, analogous to those which utilized Gunterschulze (of two flat/plane to cathode ones of disk and their encompassing orficed anodes), it was investigated also in the work [84].

The authors of this work, arguing with Gunterschulze, consider the discussed form of discharge the type of the "difficult discharge", noting, however, that until is measured field distribution between the cathodes, any line of reasoning is not founded upon solid soil. In [84] in contrast to Gunterschulze

transition into the high-voltage form of the discharge was accomplished not by reduction in current, but by the approach between themselves of cathode plates. The characteristics, which show a change in the current for aluminum cathodes, are given in Fig. 6-1.

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On it dotted lines designated the current surges which were observed with decrease of any fixed/recorded distance between the cathode plates to a value less than 0.1 mm (which was reached with the aid of the micrometric device/equipment) [1].

FOOTNOTE [1]. The difference in the numerals of amplification factor, observed during the comparison of these curves with the data of Gunterschulze (see § 3-1), the authors [84] explain by the nonobservance of the laws of similarity for the discharge with the hollow cathode (see § 3-3). ENDFOOTNOTE.

From the figure one can see that the transition from the glowing discharge to the high-voltage form in these experimental conditions is characterized by reduction in current to three orders. Transition from one form to another abrupt as transition from the glowing discharge to friend with the cathode spot. During the multiple repetition of experiments the critical distance, with which occurs

the jump, changed to value Δl=1 mm. In the limits of this spread along the distance the jump was realized either spontaneously or as a result of the decrease of distance to the minimally permitted by the conditions for experiment value on the order of 0.1 mm.

Although in the work [84], just as in [23], were not conducted any special experiments in the explanation of the mechanism of the formation/education of high-voltage discharge with the hollow cathode, nevertheless its authors postulated that this mechanism is one and the same both during the use as the hollow cathode of two flat/plane disks and in the case of usual cylindrical hollow cathode. As foundation for this conclusion/output served supplementary observations of the appearance and electrical flashover characteristics in the cylindrical hollow cathode. For the observations was selected steel cathode with an inner diameter of 10 mm. Cathode was placed in the center large-diameter of bell jar, vacuum condensed with the metallic foundation which served.

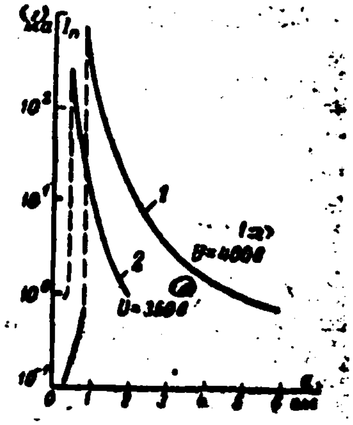

Fig. 6-1. Change in the discharge current upon transfer of glowing discharge with the hollow cathode into the high-voltage stage p=20 mm Hg. 1 - hydrogen; 2 - air.

Key: (1). mA. (2). U=400 in.

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Figures 6-2 and 6-3 show differences in the glow upon transfer from that glowing to the high-voltage hydrogen discharge. Transition was realized with gradual reduction in current, until came the moment of abrupt transition from the mode/conditions Fig. 6-2 to the mode/conditions Fig. 6-3. For the high-voltage discharge in Fig. 6-3 represented also the predicted location of equipotential surfaces whose form causes the compression of electron stream, which left the cathode into two electron beams, of the by the electrons atoms of gas

well seen with eye due to the excitation.

In the fact that the observed glowing beams are electron beams, it is easy to be convinced, placing the experimental instrument into the external magnetic field, directed perpendicularly to the axis of hollow cathode, and observing curve of the beam appearing in this case which without the magnetic field was rectilinear.

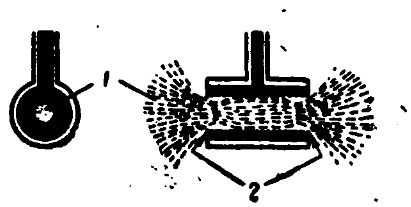

Fig. 6-2.

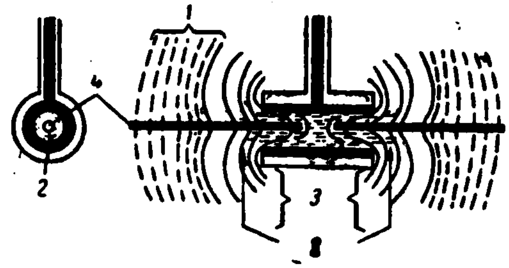

Fig. 6-3.

Fig. 6-2. Appearance of glow of glowing discharge with cylindrical hollow cathode with diameter of 10 and length 40 mm. Material of cathode - steel. Discharge was excited in hydrogen at a pressure 1 mm Hg. The external surface of cathode is covered with insulation. The picture of glow corresponds to current 100 mA and voltage/stress between the electrodes 600 V. 1 - light blue glow; 2 - pink glow.

Fig. 6-3. Appearance of glow of high-voltage discharge with cylindrical hollow cathode. Material and the sizes/dimensions of cathode are the same as for Fig. 6-2. The picture of glow corresponds to current 5 mA and voltage/stress between the electrodes 900 V. Filling - hydrogen at the pressure by p=1 mm Hg. 1 - light blue glow; 2 - pink glow; 3 - equipotentials of electric field; 4 - electron beam.

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The sufficiently strong difference in the appearance of discharge which is observed during the replacement of two flat/plane cathodes to the cylindrical cathode, led to the fact that the circle, which for the first time observed the onset of electron beam in the discharge with the hollow cathode [24], could not in its time identify the discharge observed by it with that already described earlier [23], and this was made considerably later in [84]. In [84] it was also indicated, that the difference in the appearance of two forms of the discharge in nitrogen (Fig. 6-4), which was being observed by the authors [85], is caused by nothing different as by use in the experimental tube of hollow cathode and by the onset either of the glowing or high-voltage discharge with the hollow cathode in the dependence on the ambient conditions. Thus, in spite of differences in the appearance of discharges with the hollow cathodes of different layout, all described cases [23, 24, 84, 85] relate to one type. As the most characteristic feature of a high-voltage discharge of such type in comparison with the glowing modification serves the displacement of plasma from the cathode cavity outside.

Within the hollow cathode in this case is arranged/located the cathode dark space in which there is no space-charge neutralization of electrons and ions and value of electric intensity they are great.

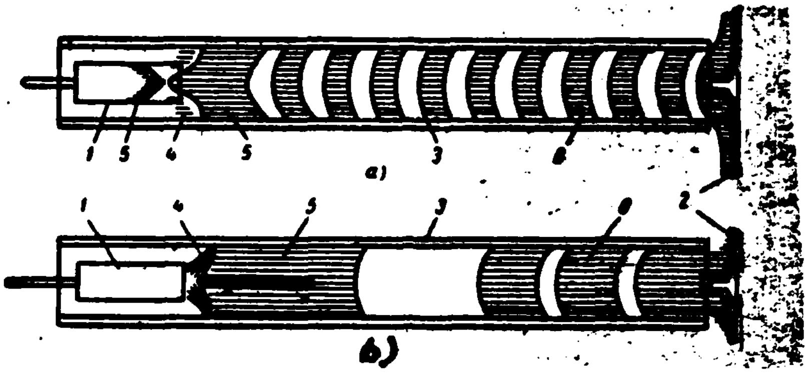

Fig. 6-4. The appearance of the glowing (a) and high-voltage (b) discharges with the hollow cathode in nitrogen. 1 - cathode; 2 - anode; 3 - the glass tube, which limits the plasma of the positive column of discharge; 4 - violet glow; 5 - yellow glow; 6 - bluish-white glow.

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The form of lines of force within the cavity is determined by the concrete/specific/actual geometry of cathode. It can be very different for the cathodes of different form, that also determines a difference in the properties of this discharge from the properties of high-voltage discharge with the flat/plane cathode, and also the strong differences, observed for the hollow cathodes of different form. During the close location of the anode to the edge of cathode cavity the plasma in the mode/conditions of high-voltage discharge can be absent not only within the hollow cathode, but also in entire

gas-discharge gap/interval. However, for the mechanism of a similar discharge the presence or the absence of plasma near the anode plays secondary role as for the flat/plane cathode [7]. Most in detail processes in the high-voltage discharge with the hollow cathode are investigated in the works of Klyarfel'd and Guseva [4, 87].

Fig. 6-5 shows one of the versions of the instruments, experimentally subjects in [4, 87]. Hollow cathode in it has a form of the beaker into which like the piston with the small gap enters the anode. The position of the anode within the cavity could be changed, so that the distance between the bottom of cathode beaker and the flat/plane working surface of the anode could be made different. For the series/row of the values of this distance were taken/removed with the aid of the electrolytic bath the pictures of electric fields in the cathode cavity which appeared under the vacuum conditions during the supplying to the anode of any voltage/stress.

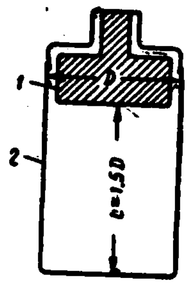

Fig. 6-5.

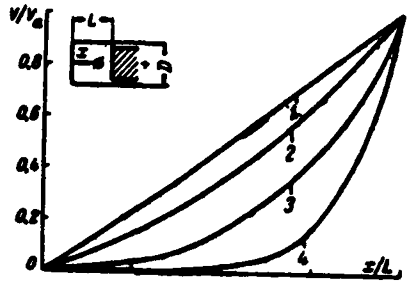

Fig. 6-6.

Fig. 6-5. Diagram of layout of electrodes in experimental instrument. 1- anode; 2 - cathode.

Fig. 6-6. Potential change along the axis of cylindrical hollow cathode for different cases. 1- L=0.25 D; 2 - L=0.5 D; 3 - L=D. 4 - L=2 D.

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Figure 6-6 gives curves of change in the potential along the axis of cathode conductor, constructed for four different positions of the anode within the cavity. It is evident that with an increase in ratio of the length of hollow cathode to its diameter the field nonuniformity within the cavity is amplified.

Fig. 6-7 gives the picture of the distribution of equipotential

surfaces and field lines in the hollow cathode, and are also shown electron paths, calculated according to the laws of electron optics. Trajectories distinctly show the tendency of electrons to form dense narrow, ray/beam in the plane, passing through the open end/lead of the cathode conductor. The analysis of the motion of ions for the conditions in question, carried out in [4], showed that as a result of the large cross section for the process of ionic charge exchange move not over the trajectories, calculated according to the rules of electron optics, but over the lines of force of electric field.

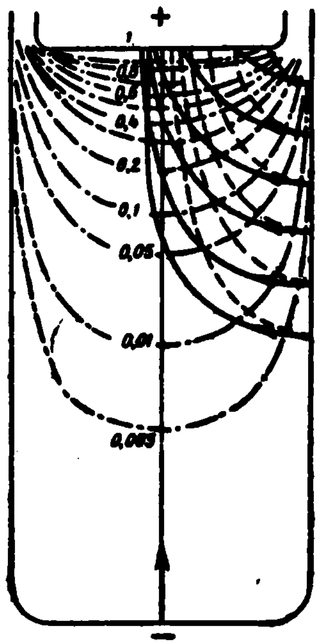

Fig. 6-7.

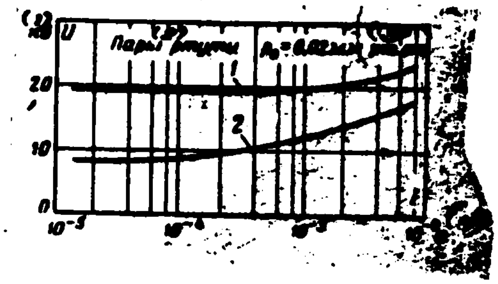

Fig. 6-8.

Fig. 6-7. Electric field and electron path for layout L=2 D. - • - • - - equipotential surfaces; - - - - - field lines; ——— - electron path.

Fig. 6-8. Volt-ampere characteristics of high-voltage discharge for layout L=D. 1 - internal electrode is positive (hollow cathode); 2 - internal electrode are negative (flat/plane cathode).

Key: (1). kV. (2). Vapors of mercury. (3). mm Hg. (4). 10^{-2} A.

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As a result of a difference in electron paths and ions satisfaction of the conditions of the self-maintenance of discharge hinders; therefore the voltage/stress of the combustion of high-voltage discharge with the equal currents proves to be higher than for the plane-parallel gap/interval. This was checked in [4] it is experimental on the same instrument by changing the polarity of the start of electrodes (Fig. 6-8). As a result of the low density of the space charges the conditions of the self-maintenance of discharge do not depend on current, if it is sufficiently small. Therefore the initial section of the volt-ampere characteristic of high-voltage discharge with the hollow cathode is the straight/direct, parallel axes of abscissas (Fig. 6-8). The lift of volt-ampere characteristic is caused either by achievement on the space charges of the significant magnitudes, or by formation/education near the anode of plasma, which narrows effective space for the ionization.

In view of this form of curves with the low currents it is possible to obtain representation about the family of the initial branches of the volt-ampere characteristics of high-voltage discharge, examining the curve of firing potentials. Fig. 6-9 gives the curves of firing potentials for the hollow cathodes of different depth, taken/removed for mercury vapor (unbroken curves). For the

comparison are given ignition curves for the case of flat electrodes (dotted curves). With the filling of experimental instrument with air were obtained analogous results.

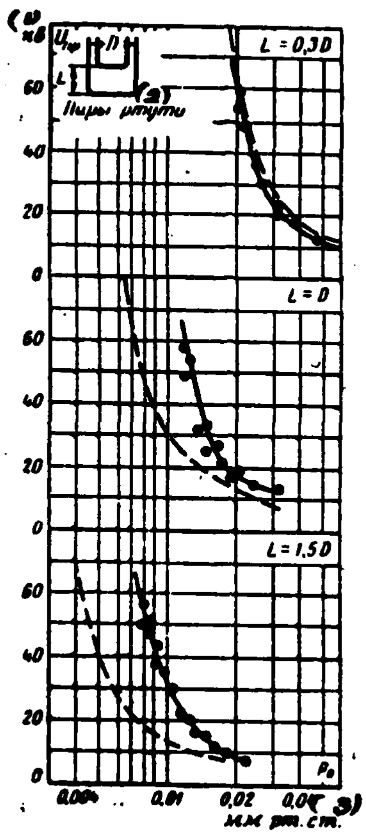

Fig. 6-9. Dependence of firing potential on the pressure for mercury vapor. D=86 mm. ——— - hollow cathode; - - - - flat/plane cathode.

Key: (1). kV. (2). Vapors of mercury. (3). mm Hg.

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From Fig. 6-9 it is evident that the greater the ratio of the length of hollow cathode to its diameter (the greater the

heterogeneity of the distribution of electric field in the cavity), the greater voltage/stress is necessary to ignite the discharge and to support it at the low currents. Qualitatively the same change in ignition curves was observed [88], also, for the inert gases in the case of replacing the flat/plane cathode by the hollow ones, performed in the form of two plane-parallel disks.

If we on the end/face of cylindrical hollow cathode supply diaphragm with the opening/aperture, and the walls of cathode to make by those penetrated for the ion flow, which go to them from the outer side, then appears somewhat different form of electron-beam discharge with the hollow cathode, for the first time described by Van Paassen and Allen [89]. Difference from the phenomena in the open cylinder is in the fact that in this case within the cavity of cathode is formed the plasma, delimited from the metallic walls by dark space of cathode drop. Plasma has positive potential with respect to the cathode of the order of several hundred volts. At the same time with the face of cathode is developed discharge with the potential of negative glow relative to the cathode of the order of several kilovolts.

Plasma cathode within the cavity supplies electrons the extracting field, which penetrates through the diaphragm. In this case precisely this system of the fields between two plasma inside

and out of the hollow cathode serves as the focusing element/cell, but not the field, formed by the walls of hollow cathode. When the plasma of the hollow cathode inside diaphragmed at the output is absent [83], this discharge form actually does not differ from the cathode-ray/electron-beam discharge with the cathode in the form of the open cylinder. When plasma within the mesh cathode exists, then between it and external plasma appears direct interaction, which leads to some specific special features/peculiarities. The ions, accelerated in the cathode dark space of external discharge, not all fall to the surface of grid, but their part passes through openings/apertures and it is introduced in the plasma within the cavity. On the other side the part of the electrons from the internal plasma is extracted through the openings/apertures and participates in conducting of the current of the external discharge.

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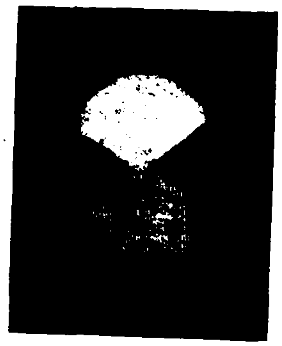
Thus, examining as the gas-discharge gap/interval only the exterior between the cathode and the anode, it is possible to visualize that the discharge is formed as a result of the multiple operation of two cathodes - metallic (its surface is equal to the total surface of wire gauze) and plasma (its surface is equal to the total surface of openings/apertures in the grid). The quantitative estimation of the effect of plasma cathode on the external discharge can be produced by

introduction for the opening/aperture of effective secondary-emission coefficient $\gamma_{эф}$ ($\gamma_{эф}$ it shows a number of electrons elongated through the opening/aperture to each ion, which passed through the opening/aperture inside the cavity). Plasma cathode under some conditions possesses considerably larger effective secondary-emission coefficient $\gamma_{эф}$ in comparison with the metallic cathode and is had a strong effect on the characteristics of cathode-ray/electron-beam discharge. The properties of plasma cathode in turn, strongly depend on external discharge.

Let us examine the special features/peculiarities of the work of high-voltage discharge with the mesh hollow cathode, following works [83, 89-95]. Fig. 6-10 and 6-11 give the photographs, which show change in the appearance of discharge upon transfer from that glowing to the high-voltage modification.



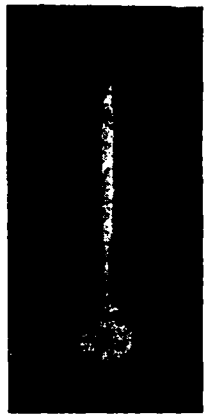


Fig. 6-10.

Fig. 6-11.

Fig. 6-10. Glowing discharge with mesh hollow cathode.

Fig. 6-11. High-voltage discharge with mesh hollow cathode.

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During the comparison with Fig. 6-2 and 6-3, which show analogous transition for the continuous hollow cathode, can be noted both the great similarity in the high-wave discharges (presence of electron beam) and difference, which is evinced by the presence within the mesh cathode of plasma, while the plasma within the continuous hollow cathode is absent. It is most convenient to analyze the connection/communication between the internal and external plasma in the case of using the spheric l mesh cathode without the special

large-diameter aperture which usually is utilized for obtaining the single powerful/thick ray/beam. Volt-ampere flashover characteristic with this geometry of cathode can be recorded in general form [95]

$$I = C_1 (U/C_2)^{C_3 p^{-h}} \qquad (6\text{-}1)$$

where C_1, C_2, C_3 and h - constants.

It was established that for the continuous spherical cathode with a diameter of 5 cm made of the stainless steel, which works in argon, the experimental characteristics (Fig. 6-12) correspond to expression (6-1), if C_1=7200, C_2=120, C_3=4.8 and h=0.282. Fig. 6-13-6-16 gives the experimental volt-ampere characteristics, taken/removed for the mesh spherical cathodes for different permeability of the used grids. All these characteristics correspond to the functional dependence

$$I_{\text{п}} = 7200 \left(\frac{U}{120}\right)^{4.8 p^{-h}}, \qquad (6\text{-}2)$$

where $I_{\text{п}}$ - current, mA;

U - voltage/stress, kV;

p- pressure, mm Hg$\cdot 10^{-3}$.

The entering formula (6-2) value h is the dimensionless quantity whose values correlate with the values of the permeability (ratio of the area, occupied with openings/apertures, to the total area), utilized for the cathode of grid.

Table 6-1.

(1) Проницаемость сетки	0,000	0,302	0,370	0,474	[illegible]
h	0,282	0,312	0,330	0,344	0,396

Key: (1). Penetrance.

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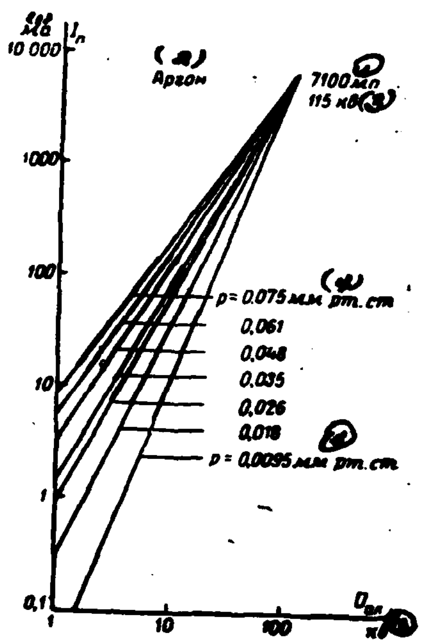

Fig. 6-12.

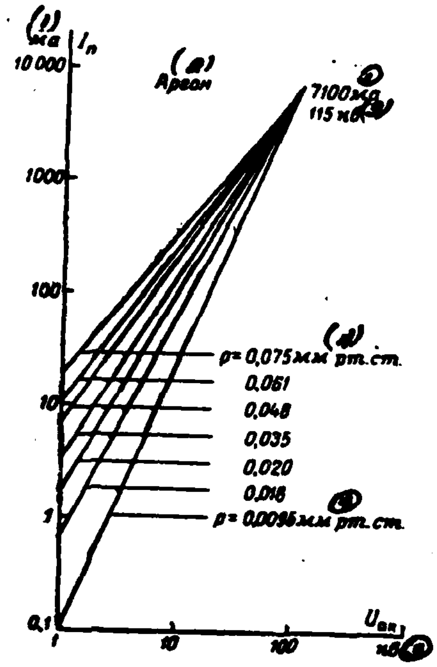

Fig. 6-13.

Fig. 6-12. Volt-ampere flashover characteristics with continuous spherical cathode. Permeability h=0.282.

Key: (1). mA. (2). Argon. (3). kV. (4). mm Hg.

Fig. 6-13. Volt-ampere flashover characteristics with mesh hollow cathode. Permeability h=0.312.

Key: (1). mA. (2). Argon. (3). kV. (4). mm Hg.

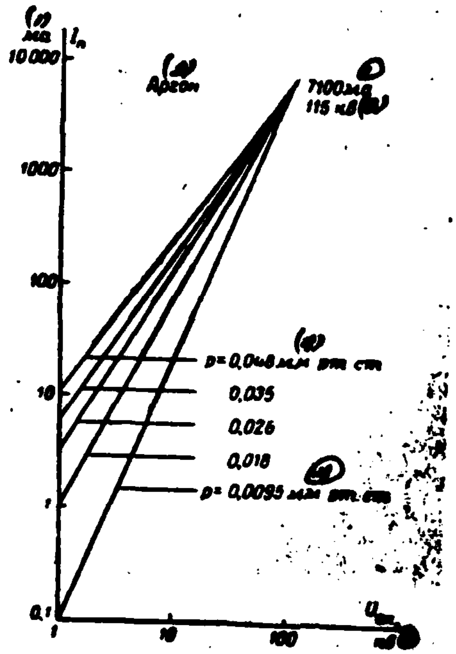

Fig. 6-14. Volt-ampere flashover characteristics with the mesh hollow cathode. Permeability h=0.330.

Key: (1). mA. (2). Argon. (3). kV. (4). mm Hg.

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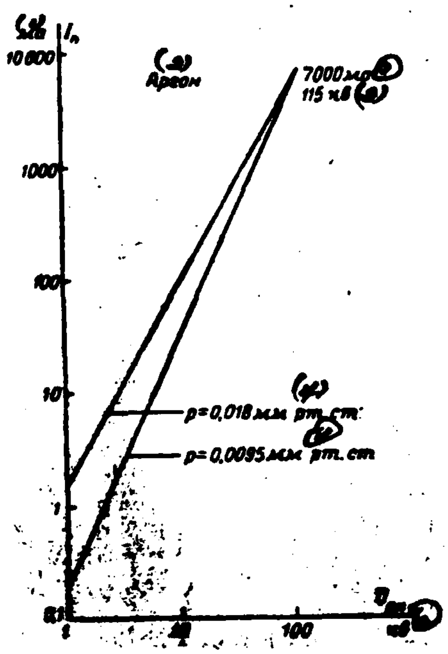

Fig. 6-15.

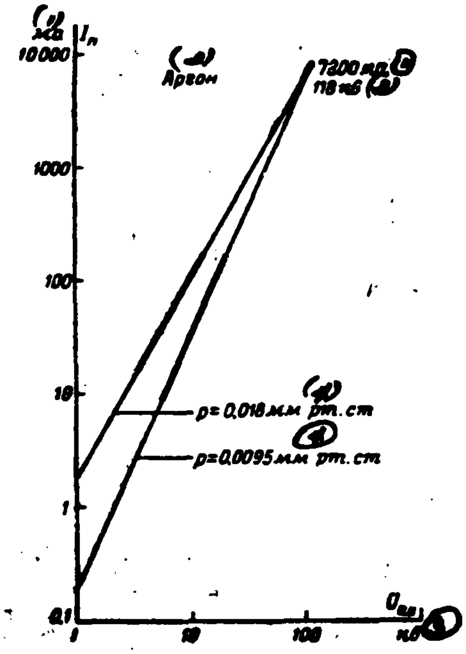

Fig. 6-16.

Fig. 6-15. Volt-ampere flashover characteristics with mesh hollow cathode. Permeability h=0.344.

Key: (1). mA. (2). Argon. (3). kV. (4). mm Hg.

Fig. 6-16. Volt-ampere flashover characteristics with mesh hollow cathode. Permeability h=0.395.

Key: (1). mA. (2). Argon. (3). kV. (4). mm Hg.

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Table 6-1 gives values h, which correspond to the values of penetrance, used for the measurement of the volt-ampere characteristics which are given in Fig. 6-12-6-16 [95]. Observing the correlation between h and penetrance gives grounds to name/call this value the "permeability of cathode".

The dependences examined show that an increase in the permeability of cathode leads to an increase in the current with the same voltage/stress. This remains valid and for the cathode-ray/electron-beam discharge which is characterized by one electron beam, which proceeds through one opening/aperture in the cathode, it is more in the value, than all rest.

The measurements of the concentration of the charged/loaded particles in the plasma within the mesh cathode by resonator shf method make it possible to make the following conclusions. At direct/constant voltage of the combustion of discharge and pressure the ionization, produced within the cathode by the ions, accelerated within the limits of the cathode dark space of the external discharge and which caught into the sieve meshes, is the increasing function of

the permeability of cathode. Figure 6-17 shows the experimental characteristics of an increase in the concentration of plasma within the mesh cylindrical cathode with direct/constant voltage and continuous change in the permeability of cathode surface.

At conclusion of this chapter it is possible to mention one more original discharge form [96, 97], which is also the modification of the high-voltage discharge with the hollow cathode, which is characterized by the multiple operation of the series/row of cavities.

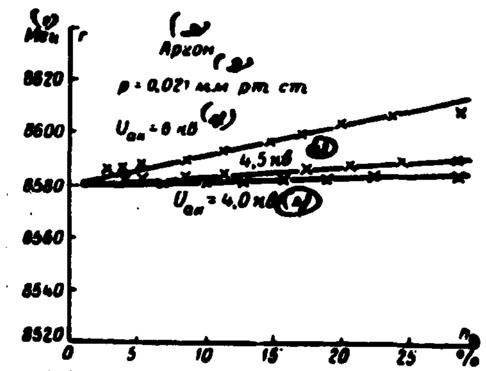

Fig. 6-17. A change in resonance frequency r (frequency shift is proportional to the density of plasma within the mesh cathode) depending on penetrance of cathode h with direct/constant voltage $U_{ан}$.

Key: (1). MHz. (2). Argon. (3). mm Hg. (4). kV.

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Chapter Seven.

APPLICATION OF DISCHARGE WITH HOLLOW CATHODE IN INDUSTRIAL ION DEVICES.

The problem of life was solved by applying the hollow cathode of almost spherical form:. This cathode worked about 15000 h, which corresponds to the service life more than of 100 years.

A. D. White [60].

1-1. Jack switches with hollow cathode.

As the commutating and indicator elements of telephone systems frequently are utilized gas-discharge instruments with the cold cathode. For example, in the United States of America several million such instruments are used in the telephone selective systems [60]. Laboratory Bell (USA) developed miniature gas-discharge diodes with

the hollow cathode and was utilized their test batch (several hundred) in the research equipment [60, 98]. The gas-discharge diodes with the hollow cathode, which work as the commutating elements/cells, revealed/detected the series/row of unique properties. As is known, to the commutating elements/cells of telephone exchange is presented the requirement to change over alternating electric currents in the range of audio frequency. For gas-discharge jack switches this indicates the imposition of such alternating currents on the direct discharge current of instrument. Therefore the important characteristic of instrument is its impedance at the audio frequency. So that the sound signals would pass through the commutating elements/cells without attenuating, impedance (impedance) of switch must be as less as possible.

It would seem better that it is possible to make in this respect - this to use the metallic contacts, which have very low resisting. However, this is not so. It proves to be that the discharge with the hollow cathode under some conditions possesses "negative resistance" for alternating current of audio frequency. This property of the glowing discharge with the hollow cathode was for the first time described in [40]. Negative resistance which indicates actually the amplification of the passing through the instrument sound signal, possibly only because in the "locked" state the gas-discharge switch the energy input from the source of direct current whose part is

converted into the intensive sound signal. In usual type discharge (the normal glow discharge with flat/plane electrodes) these properties although it is possible to obtain in the principle however their characteristics prove to be less suitable for the use/application discussed here. Thus, in the glowing discharge with the flat/plane cathode an increase in the signal frequency to 500 Hz leads to the fact that resisting of discharge no longer can be negative.

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However, in the discharge with the hollow cathode are possible the modes/conditions when negative resistance is retained at all frequencies up to 30 kHz and above.

Fig. 7-1 gives diagrammatic representation of electrodes of the experimental instrument, on which was investigated the effect of different parameters on the impedance of gas-discharge gap/interval with the hollow cathode [40]. Static volt-ampere characteristic of one of such instruments is shown in Fig. 7-2. The first negative section of this characteristic (to currents on the order of 2 mA) is analogous to the negative section of the characteristic of instrument with the flat/plane cathode. The second negative section corresponds to the range of currents 8-12 mA.

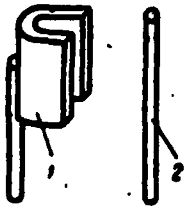

Fig. 7-1.

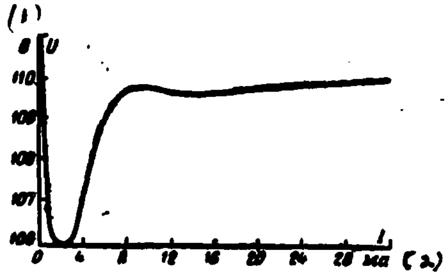

Fig. 7-2.

Fig. 7-1. Construction/design of electrodes of experimental instrument, on which were investigated flashover characteristics with hollow cathode at audio frequencies 1 - hollow cathode; 2 - anode.

Fig. 7-2. Static volt-ampere characteristic of experimental instrument, depicted in Fig. 7-1. The length of cavity is 3.2 mm, the depth of 1.6 mm, the width (a) 0.6 mm. Material of cathode - molybdenum, filling - neon, pressure - 58 mm Hg.

Key: (1). V. (2). mA.

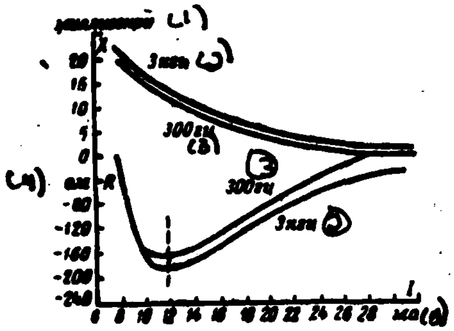

Fig. 7-3.

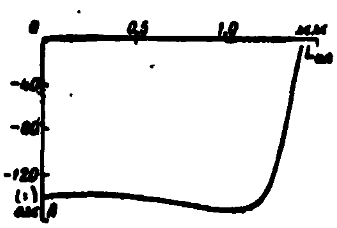

Fig. 7-4.

Fig. 7-3. Dependence of active and reactive components impedance at frequencies of 300 Hz and 3 kHz for experimental instrument. The conditions for experiment are the same as for Fig. 7-2.

Key: (1). millihenry. (2). kHz. (3). Hz. (4). Ω, (5). mA.

Fig. 7-4. Dependence of negative resistance on distance between anode and cathode of experimental instrument. The conditions for experiment are the same as for Fig. 7-2.

Key: (1). Ω.

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Dependences of active R and reactive X (inductive) components impedance on the current at frequencies of 300 Hz and 3 kHz are presented in Fig. 7-3. From the figure one can see that at these frequencies the negative active constituent R exists over a wide range of currents (8-28 mA), having maximum value for the current of approximately 12 mA.

The distance between the anode and cathode L_{ak} affects the value

of impedance. If this distance exceeds the specific value, active component becomes positive.

Fig. 7-4 presents the dependence of the active constituent of impedance on the distance between the cathode and the anode, from which it is evident that with distance $L_{\text{ак}}$ greater than 1 mm, the value of negative active constituent sharply decreases.

Fig. 7-5 gives the equivalent schematic of telephone line with the gas-discharge diode as the key/wrench. Voltage/stress on the resistance/resistor of load R_L, divided into the voltage on the load resistance/resistor in the case of the absence of the gas-discharge diode, is the measure for the attenuation, introduced into the telephone line by the gas-discharge diode, which fulfills the functions of key/wrench. This relation η, called the insertion loss of signal, is determined by the formula

$$\eta=\frac{R_S+R_L}{R_S+R_L+R_i+j\omega L_i},$$

assuming that the transformers are ideal (i.e., loss-free). At small frequencies of audio-frequency range (300-3500 Hz) of reactive component $j\omega L_i$ it is possible to disregard. Then, if the active component impedance of diode R_i is negative, value $\eta>1$, i.e., is observed not attenuation, but the amplification of the signal, transmitted by the telephone line.

Fig. 7-6 gives impedance characteristics in the dependence on the signal frequency which were obtained for the spherical molybdenum hollow cathode with a diameter of 0.075 cm, which works in neon (unbroken curve) [53]. For the comparison the same figure shows curve (broken) for the flat/plane cathode.

In Fig. 7-7 of unbroken curve it is shown, as negative resistance of discharge with the spherical hollow cathode it changes with an increase in the direct discharge current. The observed strong dependence impedance on the current of discharge is disadvantage, making it necessary to rigidly stabilize current in the instrument; however, this deficiency/lack, apparently, it can be removed by using as the working filling not one gas, but different mixtures.

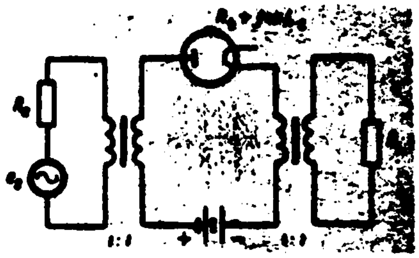

Fig. 7-5. Equivalent schematic of telephone line with gas-discharge diode as key/wrench. [illegible] - source of variable/alternating signal; [illegible] - internal resistor/resistance of source; [illegible] - load resistance/resistor; [illegible] - active and reactive components impedance of gas-discharge diode respectively.

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Effect on impedance of the discharge with the hollow cathode additions into the working gas of the admixture/impurity of helium is given in Fig. 7-7, dotted curve showed the curve of negative resistance for mixture Ne-He.

Although conditions examined above for negative resistance are ideal from the point of view of the transmission of audio signals through the switch, nevertheless for the successful creation of instrument in this case (as in many other cases of the attempts to create any instrument, which uses a discharge with the hollow cathode) this it proves to be little. Fundamental difficulty in the

operation - this is the change in the properties of discharge, caused by the strong heterogeneous pulverization/atomization of the material of cathode cavity and by the hardening of gas. Only the careful study of the properties of discharge [60] made it possible to successfully overcome the difficulty indicated. Idea consisted in the creation of long-lasting cathodes by the preliminary working of cylindrical hollow cathodes by the high-current discharge.

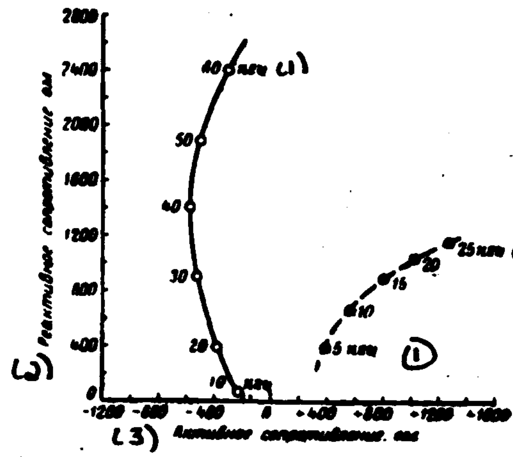

Fig. 7-6.

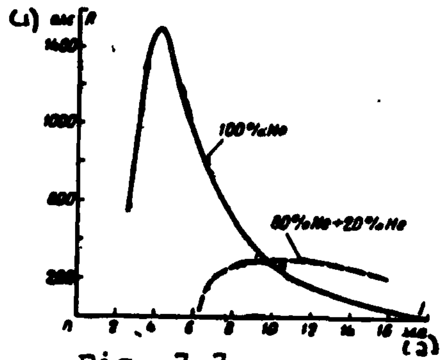

Fig. 7-7.

Fig. 7-6. Impedance characteristics of discharge with hollow (unbroken curve) and flat/plane (dotted curve) cathode.

Key: (1). kHz. (2). Reactance of ohm. (3). Effective resistance, ohm.

Fig. 7-7. Dependence of negative resistance of discharge with hollow cathode on discharge current in the case of neon (unbroken curve) and mixture helium - neon (dotted curve).

Key: (1). Ω. (2). mA.

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With some initial sizes/dimensions of cylindrical cavity

heterogeneous pulverization/atomization leads finally to shaping of the stable in the time cavity whose form subsequently does not change (see Chapter 3).

After reaching/achievement of stable form the sputtering material only is redistributed within the cavity, which is in the state of dynamic equilibrium that it leads to the considerable decrease of the hardening of gas. External characteristics of instrument with itself formed discharge itself by cathode are stable, and cathode can work very long time (on the order of 15000 h). Figure 7-8 shows the construction/design of this jack switch [60].

Although telephone switches with hollow cathode have very limited demand, nevertheless this switch is the very bright illustration of the potential possibilities of applying the discharge with the hollow cathode in the industrial gas-discharge instruments.

The gas-discharge instruments, produced at present by industry, encompass in a number of other ones stabilitron tubes, thyratrons with the cold cathode, luminous gas lamps and dischargers/gaps [99]. Let us examine the possibilities of applying the discharge with the hollow cathode in the instruments of this type.

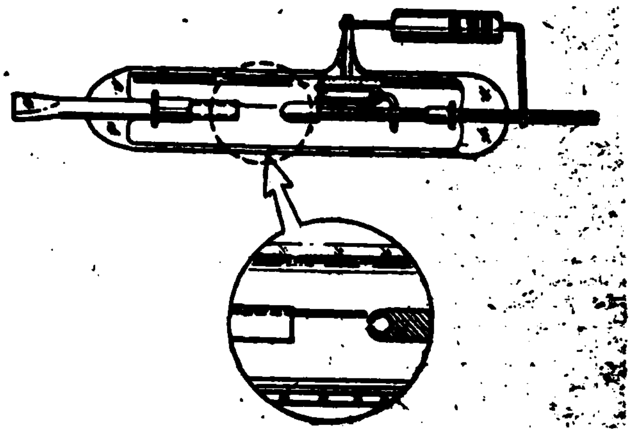

Fig. 7-8. Diagrammatic representation of industrial model of jack switch with hollow cathode and section of instrument, given in section/cut (from below) in order to show construction/design of cathode. Length of instrument of approximately 38, the diameter of 5 mm.

7-2. Stabilitron tubes and thyratrons with the cold cathode.

Properties and characteristics of stabilitron tubes and thyratrons with the cold cathode are in detail described in [100]. Usual stabilitron tubes use the horizontal (is more accurate almost horizontal) section of the volt-ampere characteristic of the normal glow discharge.

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In this case it is necessary to make the sizes/dimensions of cathode large in order to ensure an increase in the current due to an increase in the area of cathode, covered with glow. Furthermore, the propagation of discharge to the area, which was soiled/become dirty as a result of the prolonged absence of cleaning/purification by its discharge, can cause the surges of voltage/stress with an increase in the current. Two deficiencies/lacks indicated are overcome during the use of hollow cathodes [53]; however, works in this direction here will not be examined in detail, since at present there is a tendency of displacement from the industrial production of the stabilitron tubes of the glowing discharge semiconductor by instruments.

In contrast to this situation the thyratrons with the cold cathode which are used in multitube circuits of calculators, have an advantage over the transistors, since they give the light indication of the working instrument. Therefore they thus far retain their positions in the industry, and attempts at the creation of smaller/miniature instruments by replacing the flat/plane cathode by hollow are of definite interest [186].

7-3. Luminous gas lamps with the hollow cathode.

Glow-discharge glow-discharge tubes won acceptance in those areas of technology where were important the following parameters:

a) the rapid response of a change in the light parameters of instrument, not attained in the instruments, using luminous flux from incandescent solid body;

b) the spectral composition of radiation/emission.

One of such instruments where is most important the rapid response, is point source of light/world, utilized in the phototelegraphy [101, 102].

Point modulator tube of the type TMN-2. In the luminous gas lamp of the type TMN-2, used in the Soviet phototelegraphic apparatuses, is used the hollow cathode discharge. The brightness of the radiation/emission of this tube it is possible to change millions of times per second. The construction/design of the test section of tube TMN-2 is shown in Fig. 7-9. In the molybdenum cylinder which serves as cathode, is drilled cavity by diameter 1 and with the depth of 8 mm. To the cathode is put on the glass tube, in order to avoid the combustion of discharge from the external surface. Against the open upper end/lead of the cathode is arranged/located the nickel anode in the form of disk with the opening/aperture in the center. Tube with the loaded mixture of the gases: neon, argon and helium at a pressure

14-22 mm Hg. Greatest of ignition voltage for these tubes reaches 100 V, and the voltage/stress of combustion under the nominal current strength 15 mA oscillates from 105 to 135 V. The average life of tube TMN-2 is 150 h. After this time the material of cathode raising dust to the bulb bowl so weakens luminous intensity, emitted by tube, that it becomes unsuitable for its further use in the diagram of phototelegraph. Nominal luminous intensity 0.015 cd.

Light modulation is possible with the frequencies up to 1 MHz without the considerable reduction of the amplitude of transmitted pulse of light/world with the feed both by sinusoidal and square pulses.

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Spectral light sources, which use a discharge with the hollow cathode. To analyze and to describe entire variety spectral of the sources with the hollow cathode, used in 50 years, which passed from the day of its discovery/opening by Paschen, does not enter into our problem. We will be restricted only to indication of works [13, 103-105], in which are systematized main trends and successes in this region, and are also outlined the basic features of constructions/designs and special feature/peculiarity of the work of the applied hollow cathodes. In somewhat more detail let us examine

only the spectral sources with hollow cathode, which solve general research problems.

To such sources belong the standard sources of the spectrum and the sealed sources for the atomic-adsorption measurements. The essential requirements, presented to these instruments, are simplicity of construction/design, which ensures the rapid exchange of tubes, large service life, minimum time of preliminary training to obtaining of stable radiation/emission and reproducible character of the spectra. The fact that the discharge lamps with the hollow cathodes are the very stable sources of the excitation of the spectra with the thin spectral lines, long ago is known very. However, long time was considered that for the normal operation of source with the hollow cathode was necessary the vacuum system, which makes it possible to clean working gas from the admixtures/impurities, which are isolated from the metallic parts of the tube, and to periodically replace working gas. And only in 1955 in the works [41, 106] proposed the construction/design of the sealed tube with the hollow cathode, which was intended for the prolonged operation isolated/insulated from the vacuum system.

Similar tubes were recommended [41, 184] for using as the standards the wavelengths and intensity of light. Usually as the standard source of the spectrum is utilized the arc discharge with

iron electrodes, which works in the atmosphere. This selection is caused by the ease/lightness of obtaining a similar spectrum and by the fact that it consists of very many closely spaced spectral lines, which overlap entire visible and ultraviolet region up to 2500 Å. The wavelengths of the spectrum of iron repeatedly thoroughly were measured and many of them were proposed as international standards. From the very beginning of use of this spectrum as the standard came to light its deficiencies/lacks. It turned out that the wavelength is not strictly constant, but it depends on the method of arc-striking. This leads to the need to strictly observe the specified conditions for arcing. But even in this case it was necessary to exclude many lines the wavelength of which nevertheless strongly was changed. Further, arc does not always burn stably, it can change its position relative to slot, and as a result exposure is obtained first of too strong, then of the too weak.

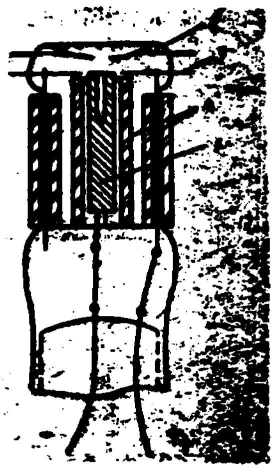

Fig. 7-9. Diagrammatic representation of point modulator tube TMN-2. 1 - hollow cathode; 2 - anode; 3 - mica; 4 - glass.

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The width of the lines, emitted by arc, is such, that the very precise interferometric determinations of wavelength cannot be made.

Work experience [41] on the spectrographs with the large gratings showed that the use as the standard of arc on the iron electrodes is the most important source of errors. These enumerated deficiencies/lacks are sufficiently essential; therefore there were many propositions about the use of other standards, moreover fundamental changes concerned the method of exciting the spectrum of iron, but not material change, since by itself the spectrum of iron is sufficiently convenient.

However, new standards usually possessed other sufficiently essential deficiencies/lacks, so that they for a long time could not compete with another. In particular, discharge with the hollow cathode was proposed as the source of the standard spectrum as early as 1939 [107]. However, in view of the need for vacuum system for maintaining the stability of the spectrum source with the hollow cathode proved to be too inconvenient and bulky for its wide acceptance.

Proposed in [108] getter from activated uranium gave the simple resolution of the problem of the possibility long time to work with the sealed tube without the disturbance/breakdown of its spectral cleanliness by admixtures/impurities. The use/application of this getter in the source with the hollow cathode and the investigation of its properties allowed the authors [41] to arrive at the conclusion that a similar source has in practice in every respect the irrefutable advantages over the arc in the atmosphere during its use as the standard of wavelengths. This tube can be successfully utilized, also, as the standard of intensity.

The construction/design of standard source with the hollow iron cathode technology of production of which is in detail described in [41], it is shown in Fig. 7-10.

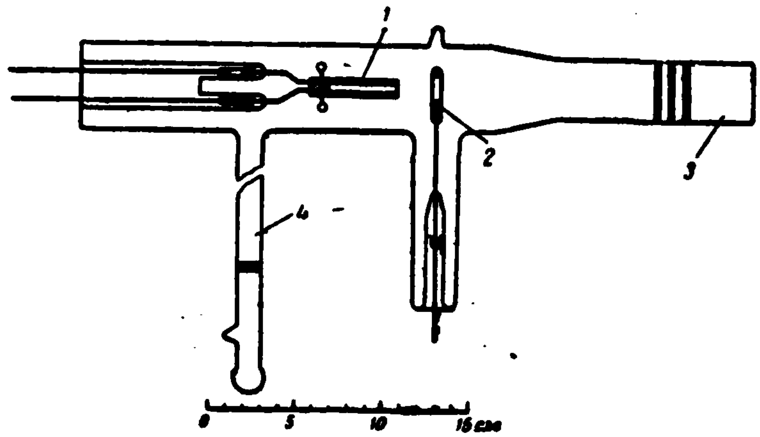

Fig. 7-10. Diagrammatic representation of standard of wavelengths on hollow cathode. 1 - hollow cathode; 2 - anode in the form of ring; 3 - quartz window; 4 - getter.

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This source works with currents on the order of 100 mA and voltages/stresses several hundred volts. Ignition voltage of approximately 300 V. The filling of tube - neon at a pressure 3 mm Hg, with which is obtained the most intense spectrum. Service life of tube is approximately 1000 h. Only deficiency/lack in this source in comparison with another in the atmosphere - its small brightness (approximately/exemplarily 100 times less). However, this is not very large deficiency/lack, since the time of exposure even for the very large spectrographs with the use of hollow cathode rarely exceeds 20 min.

Steady-state burning and absence of any need for following the source during the exposure completely redeems the elongation of the time of exposure. Moreover, the actual ratio of the times of exposure is less than 100:1, since lines in the hollow cathode are weakly widened and do not test/experience self-absorption. Experiments showed that the sealed standard source does not detect the fluctuations of intensity for the hours or even days of work. Consequently, it can serve as the source of comparison spectrum with the work with the photomultipliers and as the photodiodes where is essential stability both into the short ones and into the prolonged time intervals. The nonremovable fluctuations of intensity in the arc standard source are made with its completely unsuitable for these purposes. The stability of intensity during the calibration of photographic plates also differ significantly standard source with the hollow cathode from the arc source. If we the described source utilize as a standard of intensity, then is important the stability of intensity during entire service life. The fundamental source of a gradual change in the intensity - this is the hardening of the filling gas.

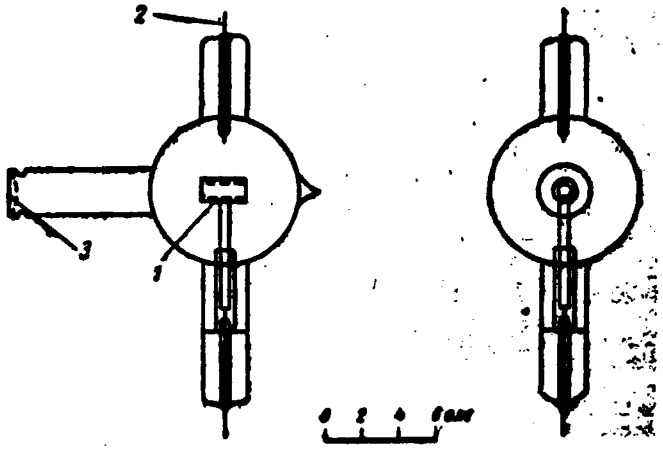

Fig. 7-11. Tube with hollow cathode for atomic-absorption measurements. 1 - hollow cathode; 2 - anode; 3 - uviol window, transparent to 2100Å.

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No simple methods of the completion/replenishment of neon in the sealed tube are not developed. However, to monitor a change in the pressure is possible via the comparison of the ratio of the intensities of any pair of lines with its initial value. Divergence of 3-4% became too low and tube no longer can be used as the standard of intensity. For using as the standard the intensity can be more preferably the filling of tube not neon, but by krypton. In this case the condensation of krypton in the special tap at a temperature of liquid nitrogen (77°K) maintains in the tube the constant/invariable pressure of krypton of approximately 1.6 mm Hg. Pressure is not

changed with the hardening of gas, since it is the pressure of saturated vapors of the condensed phase of krypton.

The sealed tubes with the hollow cathode, similar as that described above can serve not only as the standards. In Leningrad the colleagues of GOI developed [109] the sealed tubes with the hollow cathode for the atomic-absorption measurements and the production of a spectrum of comparison [86, 109, 185]. The construction/design of the developed tubes is shown in Fig. 7-11. Cathode is manufactured from the one-piece/entire piece of the metal of a sufficient cleanliness and is cylinder with through opening. The sizes/dimensions of the cavity: the diameter of 6 mm, the length of 20 mm, the wall thickness of cathode is 2.5 mm. For the radiation yield is used the thin uviol glass, transparent to 2100Å. As the material of cathode are used the materials: Al, Bi, Ca, Cd, Co, Cr, Cu, Fe, Mg, Mo, Ni, Pb, Sb, Sn, Ti and Zn. This set/dialing is caused in essence by the requirements of the atomic-absorption spectral analysis. A voltage drop across the electrodes of the described sources with the hollow cathode usually 200-300 V, the ignition voltage on the order of 400-500 V, noises of the luminous flux do not exceed 0.1%. The stability of the radiation/emission of these tubes was checked [109] for the tube with the iron hollow cathode, filled with neon. Were measured the fluctuations of the intensity of line Fe 3720Å on different levels of the luminous flux, which falls to the

photomultiplier, and it was shown that the recorded fluctuations were connected with the shot effect of receiver, but not with the internally-produced noise of tube. On the basis of this it is assumed, that the higher noise level (to 1%) of tubes with the hollow cathodes, recorded, for example, in the work [110], is connected with the negligible shot effect of receiver.

7-4. Superhigh-frequency dischargers/gaps with the hollow cathode.

Receiver and transmitter of radar, as a rule, work with one antenna; therefore at the moment of the work of transmitter antenna must be disconnected from the receiver in order not to injure its input cascades/stages by the large power, emitted during the transmission. Usually for the protection of receiver serves resonance discharger. With the passage of large power from the transmitter in the direction of antenna resonance dischargers of discharger/gap will be short-circuited by the plasma, formed as a result of the superhigh-frequency breakdown of gas gap of instrument.

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The density of this plasma and its location in the plumbing are such, that the energy, which goes from the transmitter, is reflected from the layer of plasma and it does not reach receiver. In the reception

mode the signals freely pass through the discharger/gap to the receiver because their energy is insufficient for the breakdown of gas gap. From this schematic of the work of resonance discharger it is clear that the protection of receiver in this case always retarded. In the period when occurs superhigh-frequency breakdown and the plasma of high concentration yet was not formed, the considerable portion of power (called leakage power) falls to the input of receiver.

If it is necessary to completely remove leakage power, are applied not the resonance, but controlled dischargers/gaps, in which the plasma is created from the special external source somewhat the previously beginning of transmission. Thus when powerful/thick signal the plasma of necessary density in the discharger/gap is already formed. Usually in the controlled dischargers/gaps is used positive glow-discharge column.

However, in [111, 112] it is shown that the use instead of the positive column of the zone of negative glow can give the series/row of the advantages, caused by the fact that the density of the charged/loaded particles in this zone to two orders is more, and collision rate by an order is less than in the positive column. A deficiency/lack in the instruments with negative glow is the technical difficulty of the introduction of cathode inside the

waveguide and deterioration in parameters of discharger/gap, important in the reception mode, caused by the presence within the waveguide of the cathode and other structural elements/cells. These deficiencies/lacks are removed with the use of plasma within the hollow cathode which serves waveguide itself. As an example of use of the plasma of hollow cathode in the passive gas-discharge superhigh-frequency instruments can serve the attenuator, described in [113]. Its construction/design is schematically shown in Fig. 7-12. Hollow cathode is entire/all internal surface of waveguide. The anode in the form of stub is carried out beyond the limits of waveguide and is arranged/located opposite the opening/aperture in the wall of waveguide. Within the waveguide there are no structural elements/cells, besides the sealing windows.

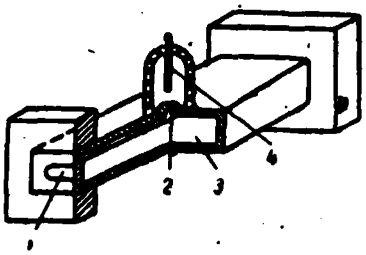

Fig. 7-12.

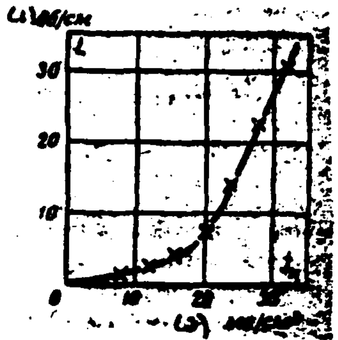

Fig. 7-13.

Fig. 7-12. Gas-discharge attenuator with hollow cathode. 1 - sealing window; 2 - opening/aperture in the wall of waveguide; 3 - surface of hollow cathode; 4 - anode.

Fig. 7-13. Dependence of attenuation on 1 cm of length on current density on cathode.

Key: (1). dB/cm. (2). mA/cm².

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Fig. 7-13 gives the experimental dependence of attenuation on 1 cm of length on the current density on the cathode j_k, obtained for the kovar hollow cathode with a cross-section of 7.2×3.4 mm with the filling of instrument with helium up to a pressure of 50 mm Hg [113]. From the figure one can see that an increase in the current density from 20 to 30 mA/cm² leads to an increase in the attenuation from 7 to 27 dB/cm.

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